THE ASTROPHYSICAL JOURNAL, 358: L63–L67, 1990 August 1

ACCELERATION OF ENERGETIC PARTICLES BY SHOCK WAVES FROM LARGE SOLAR FLARES

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Received 1990 March 21; accepted 1990 May 18

ABSTRACT

The observations in large "solar" proton events are discussed in terms of acceleration of the energetic particles from the ambient solar wind by an interplanetary shock. Many of the large events are found to have a prolonged plateau in their time-intensity profiles. The same value of the intensity, near 100 protons (cm^2 sr s MeV)$^{-1}$, seems to recur in the plateau region in all of these events. These profiles are explained by models of prolonged acceleration by an interplanetary shock. At some distance from the shock, when the particle intensity falls to a value that is sufficiently low, particles stream away from the source with relative ease. The observed profiles are not consistent with models involving particle transport from a single localized point source at the Sun.

Element abundance ratios such as Fe/O usually distinguish flare-heated source material (Fe/O $\sim$ 1) from material accelerated by the interplanetary shock out of the ambient corona or solar wind (Fe/O $\sim$ 0.1). In several large events that are magnetically well connected to the flare site, Fe-rich material from the flare is observed early in the event, followed by Fe-poor material. Observation of these two-component events requires a well-connected flare, since the Fe-rich material does not have access to field lines far from the flare. The observations argue against any mechanism for cross-field particle transport in the solar corona.

Subject headings: particle acceleration — shock waves — Sun: abundances — Sun: flares — Sun: solar wind

I. INTRODUCTION

For many years it has been known that coronal and interplanetary (IP) shocks can accelerate protons to energies as high as $\sim$1 GeV (see review by Forman, Ramaty, and Zweibel 1985). Lee and Ryan (1986) calculated the temporal and spatial dependence of energetic particles accelerated by a spherical shock expanding into an interplanetary medium with density decreasing as r^{-2}. They found that protons could be accelerated to 10 MeV in tens of seconds and to 1 GeV in tens of minutes, with the acceleration continuing as the shock propagates out as far as 1 AU. Lee and Ryan (1986) considered particle scattering by ambient Alfvén waves. However, Reames (1989) recently suggested that self-generated waves may also contribute to the scattering of 1–10 MeV particles streaming away from large events after a sufficient time. The high anisotropies and fast time profiles observed in small impulsive-flare–related events suggest that the ambient wave intensity produces little scattering on a time scale less than λ/v which can be several hours when the IP scattering mean free path λ is $\geq$1 AU (Reames 1989 and references therein).

A recent study of observations in 235 proton events occurring over a time period of 20 years led Cane, Reames, and von Rosenvinge (1988) to conclude that IP shocks play a significant role in particle acceleration in large events, even at relatively high energies. Those authors note that the most intense events come from flares near central meridian, as do the strongest shocks, rather than from a longitude of 50°–60° W when Earth has the best magnetic connection to the flare. For particles above 1 MeV, the effects of the shock were usually nonlocal, in the sense that the greatest intensities occur when the observer is magnetically connected to the strongest region of the shock and not when a weaker portion of the shock passes the spacecraft.

Observations on the abundances of elements at energies above 2 MeV amu^{-1} have shown a bimodal distribution in the Fe/O ratio (Reames 1988; Reames, Cane, and von Rosenvinge 1990; see review by Reames 1990). The Fe-rich (Fe/O $\approx$ 1.0) events have been associated with impulsive flares from which highly ionized (Luhn *et al.* 1987) hot material is ejected while the Fe-poor (Fe/O $\approx$ 0.1) material is accelerated by a shock from the cooler ambient gas in the corona or the solar wind.

This *Letter* calls attention to observational evidence that the time-intensity profiles of protons in large solar flare events are often well described by the extended, flat profiles calculated by Lee and Ryan (1986). Furthermore, the element abundance data in large well-connected flares often separates flare and IP shock–related components in a way that further demonstrates the importance of acceleration by the IP shock.

II. PROTON OBSERVATIONS

The Goddard Cosmic-Ray Experiment on the *Helios 1* spacecraft (Trainor *et al.* 1984; McDonald and Van Hollebeke 1985) is ideally suited to the observation of protons in large solar energetic particle (SEP) events. Relatively small geometry factors and fast electronics render the experiment nearly immune from the saturation effects that often plague the more sensitive experiments on near-Earth spacecraft. A sample of large SEP events was collected by scanning the *Helios 1* particle data base for the 1974 to 1984 time period for significant increases in the intensity of 135–206 MeV protons. The onsets of these increases provided a sufficiently accurate measure of the flare time for studies of the lower energy time-intensity profiles. The largest 14 events were selected for study.

A particularly interesting time-intensity profile is seen in the 1979 February 16 event shown in Figure 1. Such prolonged flat profiles are also found among the profiles calculated by Lee and Ryan (1986) for continuous acceleration by a traveling IP shock as it moves outward from the Sun. Such a profile would

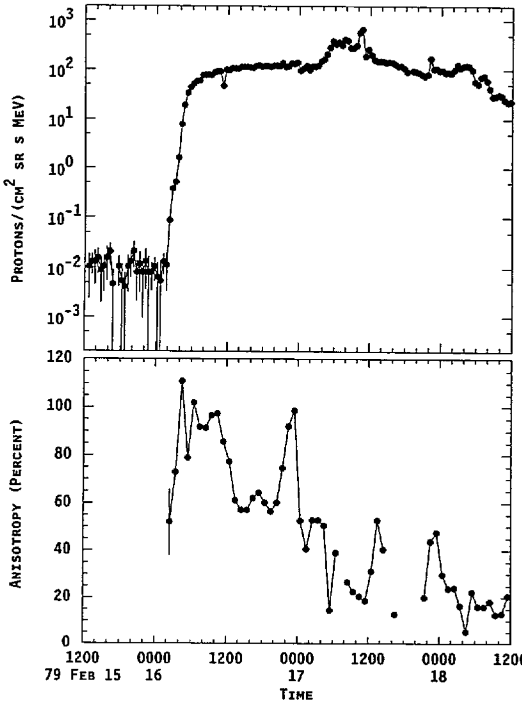

FIG. 1.—A time-intensity profile of 3–6 MeV protons observed on the *Helios 1* spacecraft at 0.98 AU is shown in the upper panel. Flat extended profiles like this have been predicted by the IP shock model of Lee and Ryan (1986). The lower panel shows the anisotropy (coefficient of cos θ) of these protons (see text).

be extremely difficult to generate by a transport-dominated model with impulsive injection of particles at the Sun.

The particle anisotropy during the 1979 February 16 event is also shown in Figure 1. The anisotropy begins to decline rapidly about 4 hr after the intensity reaches a plateau value near 100 protons (cm^2 sr s MeV)$^{-1}$. This time scale is consistent with the time required for local wave generation by the streaming particles (Reames 1989); however, the anisotropy does not go to zero on the initial decline, as one might expect. It is possible that the second increase and rapid decline in anisotropy late on February 16 represents a new injection of particles; however, the intensity remains remarkably stable at ~ 100 protons (cm^2 sr s MeV)$^{-1}$. Rapid declines in anisotropy early in large events have been reported previously (Evenson and Meyer 1979).

A collection of time-intensity profiles is shown at two different energies in Figure 2. Most of the low-energy profiles share some of the behavior of the 1979 February 16 event in that the intensities rise rapidly to a value near ~ 100 protons (cm^2 sr s MeV)$^{-1}$ and then flatten abruptly. In some of the events, the low-energy proton intensity rises again later in the event and reaches a maximum near the time of passage of the IP shock. In these later peaks, the *Helios* experiment responds easily to intensities that are nearly two orders of magnitude larger than that on the earlier plateau. Clearly, the flattening near ~ 100 protons (cm^2 sr s MeV)$^{-1}$ early in the events is not an instrumental limit. Other events, discussed in the next section, also show the same intensity plateau for low-energy particles.

The low-energy time-intensity profile of the 1982 June 3

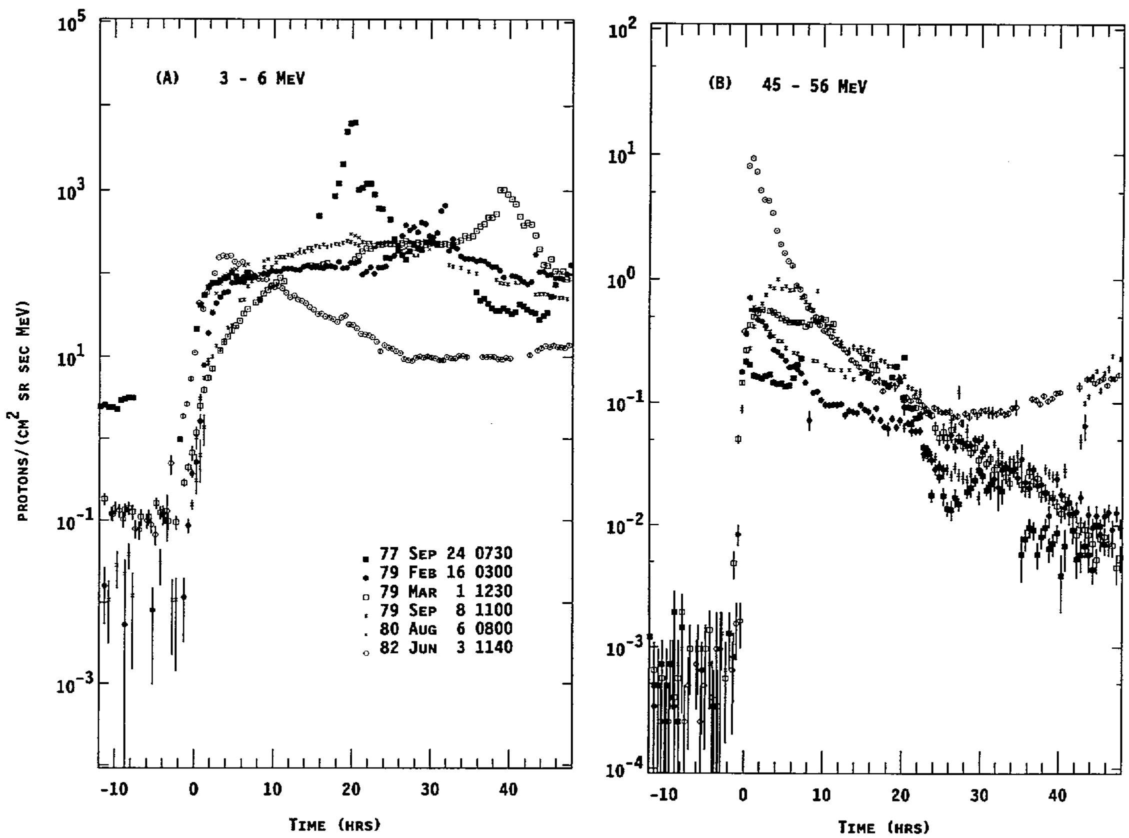

FIG. 2.—Superposed time-intensity profiles (30 minute average) are shown for several *Helios 1* events at two different proton energies. Offset times of the events are listed. The first and last events listed were observed when the spacecraft was at 0.59 and 0.57 AU, respectively; the remaining events were observed at 0.93–0.98 AU. Intensities of low-energy protons tend to reach a plateau near ~ 100 protons (cm^2 sr s MeV)$^{-1}$ early in the event.

event is unlike the others in Figure 2 in that it has the more typical rise and decay profile commonly associated with impulsive particle acceleration at the Sun. The 1982 June 3 event is the largest of several events that have this behavior. This event has been included in Figure 2 to contrast its profile with those of the other events and to illustrate that even large impulsive flare events do not seem to exceed the ~ 100 protons (cm^2 sr s MeV)$^{-1}$ intensity value early in the event.

III. HEAVY-ELEMENT ABUNDANCES

While most large proton events have low Fe/O throughout the event, the three events shown in Figure 3 have high values of Fe/O early in the event followed by low values late in the event. For each event in the figure, the intensities of O and Fe observed in two energy intervals by the Goddard experiment aboard the *ISEE 3* spacecraft (von Rosenvinge *et al.* 1978) are shown in the top panel together with 4–6 MeV proton intensities from the *IMP 8* spacecraft (McGuire, von Rosenvinge, and McDonald 1986). Fe/O ratios are shown in the lower panel for three energy intervals whenever the error in the ratio is $\leq 50\%$ of the ratio itself. The high values of Fe/O ~ 1.0 seen early in the events in Figure 3 are attained consistently at all energies where measurements have been made. Soon after the proton intensities reach ~ 100 protons (cm^2 sr s MeV)$^{-1}$, Fe/O begins to decline and eventually reaches a value near 0.1. These events are therefore understood as a composite of a flare-associated ion population followed by an IP shock accelerated population.

It would be misleading, however, to leave the impression that a single measurement of Fe/O is adequate to completely define the origin of the particles. The 1978 September 23 event, shown in Figure 4, illustrates the perils of such an interpretation. This event has a relatively high value of the Fe/O ratio at 2–3 MeV amu^{-1} but a much lower value at high energies. However, measurements of the ionic charge state of Fe during this event (Hovestadt *et al.* 1982) show an average charge of 13.5 ± 0.5, and the daily averaged charge state remains essentially constant throughout the event (B. Klecker, private communication). This low charge state is consistent with acceleration of the particles from the ambient solar wind rather than from flare-heated material which gives rise to Fe with a typical charge of 20 (Luhn *et al.* 1987). Note, however, that the 1978 September event in Figure 4 shows a steep decrease in Fe/O with energy just when the low-energy Fe/O ratio is high, while the events in Figure 3 show the same high ratio at all energies early in the events due to acceleration of material that is already Fe-rich as a result of selective preheating by preferential absorption of waves. While charge state measurements are not available for the events in Figure 3, the constancy of Fe/O with energy suggests that the enhancement of Fe is a property of the preheating phase and not the acceleration phase.

IV. DISCUSSION

For several years there has been increasing evidence of two distinct populations of energetic particles in association with solar flares. The profiles and abundances seen in the large events add new evidence to this picture. We find that many of the large "solar proton events" are, in fact, dominated by acceleration of material from the solar wind by the *interplan-*

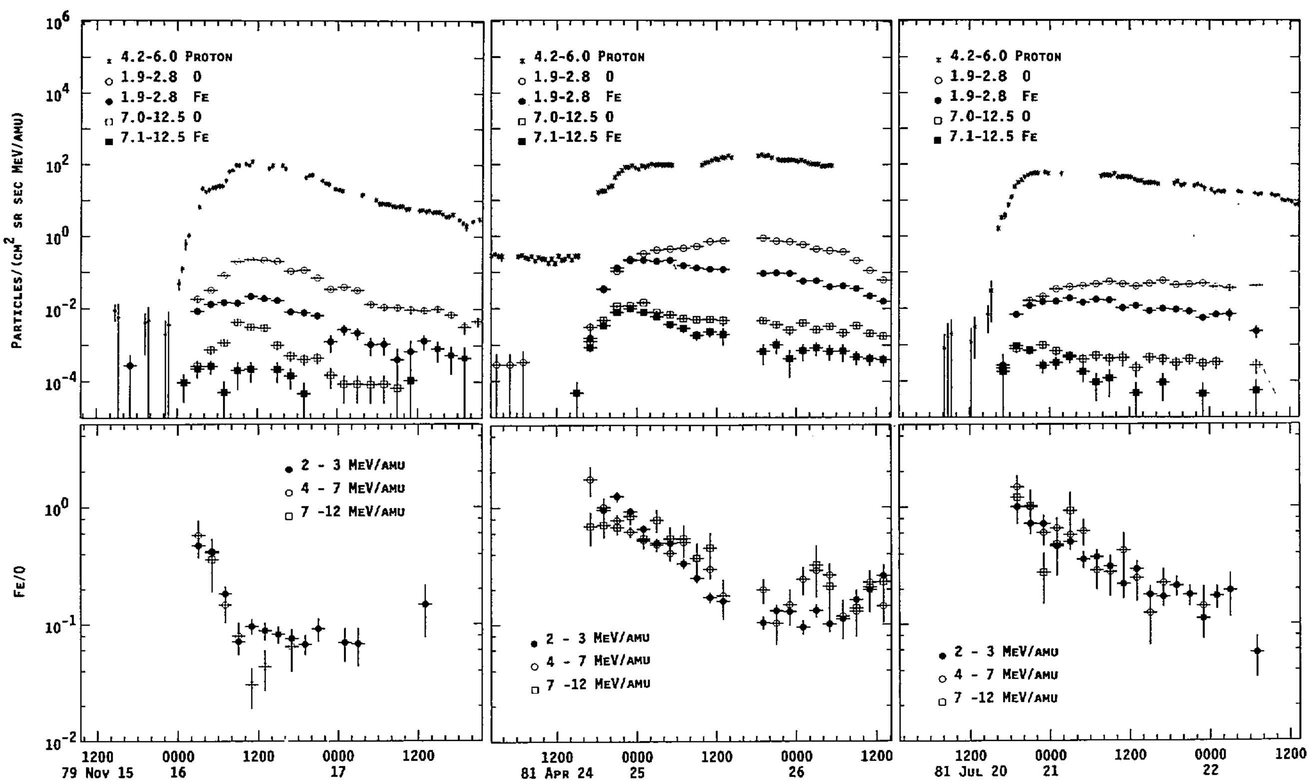

FIG. 3.—Time-intensity profiles of protons and O and Fe ions are shown in the top panels for three events. The time variation in the corresponding Fe/O ratios are shown in the lower panels. The energy-independent Fe-rich material arriving early may come from the impulsive flare, while the following Fe-poor material is accelerated later by the IP shock.

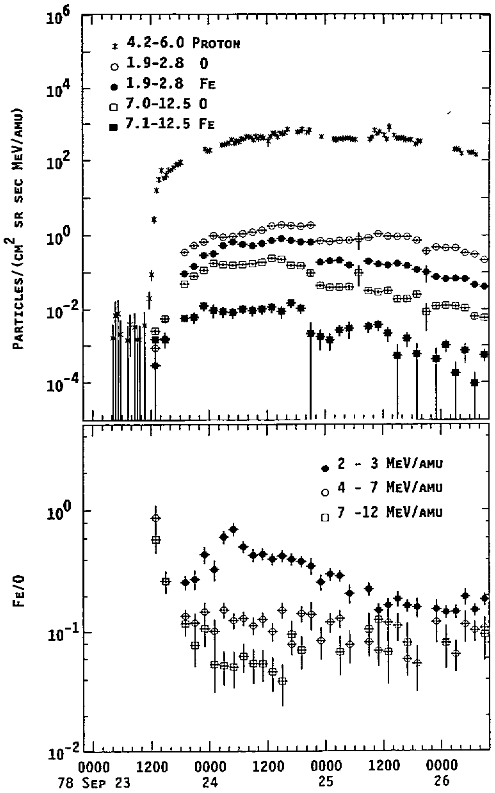

FIG. 4.—Proton, O, and Fe intensities similar to those in Fig. 3 are shown for the 1978 September 23 event. The weak energy-dependent Fe enhancement that peaks 18 hr after the event onset contrasts with those in Fig. 3. Differential acceleration by the shock probably causes the energy-dependent Fe/O ratio shown in the lower panel.

etary shock. These shocks cross magnetic field lines to accelerate particles in regions that are not connected to the flares. In well-connected events, both flare- and shock-associated particles can be distinguished.

The theory of Lee (1983) describes the manner in which particles are accelerated as they are trapped near a shock by scattering against self-generated Alfvén waves that are produced as the particles begin to stream away from the shock. Near the shock, the high particle intensities can cause a high growth rate for waves, and an equilibrium is established where the intensities depend only upon distance from the shock. This nonlinear process will occur at any energy once the intensities of the streaming particles are sufficiently large. Upstream of the shock, the intensities of the particles decline and the growth time scale of the waves becomes sufficiently long that the particles begin to stream freely away. Evidently this point is reached at an intensity corresponding to 100 protons (cm^2 sr s MeV)$^{-1}$ near Earth (Reames 1989). The model of Lee and Ryan (1986) does not include wave generation by the particles; however, it does produce broad particle profiles as a result of protracted acceleration by the shock.

High-energy particles, as well as low-energy particles, are also accelerated by the IP shock in large proton events. Kahler, Reames, and Sheeley (1990) note that the intensities of high-energy particles often peak when the coronal mass ejections (CMEs) and the IP shocks that they drive have reached distances of 8–10 solar radii, well above the solar corona. Observations of the angular distributions of particles near shocks at 1 AU show particles streaming away from the shock in both the upstream and downstream regions (Richardson, Cane, and von Rosenvinge 1990). All of these observations associate particles of over 100 MeV with shock acceleration.

Generally, large shock-associated events have values of Fe/O that are near the coronal or solar wind value (e.g., Meyer 1985). In some events, like the 1978 September 23 event shown in Figure 4, the spectrum of Fe ions is steeper than that of O ions so that Fe/O is large only at low energies. This phenomenon, which, presumably results from rigidity dependence of the acceleration, was noted previously by Klecker *et al.* (1981) and was discussed by Lee (1983). In other events, shown in Figure 3, we see evidence of Fe-rich, impulsive-phase material that arrives before the Fe-poor material from the shock. The three events in Figure 3 are all from magnetically well-connected flares on the Sun at longitudes 35° W, 50° W, and 75° W, respectively. The Fe-rich component is only seen in well-connected western events, suggesting that the material cannot cross field lines.

In large events it is, perhaps, surprising that the energetic Fe-rich material from the flare does not serve as a "seed population" for the ensuing IP shock. There is evidence (Van Hollebeke, McDonald, and Meyer 1990) that the coronal shock does accelerate Fe-rich material in events like the large 1982 June 3 event which has metric type II radio emission from the coronal shock, but it lacks a strong IP shock. Cane and Reames (1988) distinguish the coronal shock as a blast wave from heating that may occur in the flaring loop while the IP shock is driven as a bow shock of the CME. Many impulsive Fe-rich events show evidence of type II bursts. These coronal shocks may further accelerate the particles without significantly altering their abundance. Generally the IP shocks do not have access to the Fe-rich material from the impulsive phase, because they traverse field lines that are not connected to the flare site.

I would especially like to thank H. V. Cane for numerous helpful discussions on the consequences of IP shocks throughout the course of the work. I also appreciate discussions with F. B. McDonald on the *Helios 1* observations, and I thank T. T. von Rosenvinge for discussons and for his comments on the manuscript.

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